

DRAGONS – A Micrometeoroid and Orbital Debris Impact Sensor

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ABSTRACT

The Debris Resistive/Acoustic Grid Orbital Navy-NASA Sensor (DRAGONS) is intended to be a large area impact sensor for in situ measurements of micrometeoroids and orbital debris (MMOD) in the millimeter or smaller size regime. These MMOD particles are too small to be detected by ground-based radars and optical telescopes, but are still large enough to be a serious safety concern for human space activities and robotic missions in the low Earth orbit (LEO) region. The nominal detection area of a DRAGONS unit is 1 m², consisting of several independently operated panels. The approach of the DRAGONS design is to combine different particle impact detection principles to maximize information that can be extracted from detected events. After more than 10 years of concept and technology development, a 1 m² DRAGONS system has been selected for deployment on the International Space Station (ISS) in August 2016. The project team achieved a major milestone when the Preliminary Design Review (PDR) was completed in May 2015. Once deployed on the ISS, this multi-year mission will provide a unique opportunity to demonstrate the MMOD detection capability of the DRAGONS technologies and to collect data to better define the small MMOD environment at the ISS altitude.

1. INTRODUCTION

The NASA Orbital Debris Program Office (ODPO) has been supporting the development of particle impact detection technologies since 2002 [1, 2]. The ultimate goal is to conduct in situ measurements to better characterize the small micrometeoroid and orbital debris (MMOD) populations in the near-Earth environment, especially in low Earth orbit (LEO, the region below 2000 km altitude) where many critical NASA spacecraft, including the International Space Station (ISS), operate. Due to the high impact speed in LEO (with an average of 10 km/sec), orbital debris as small as 200 μ m are a safety concern for human space flight and robotic missions. Similar risks also come from small micrometeoroids (but with higher impact speeds). To define the orbital debris environment to cover the entire spectrum of the population, different observational approaches are needed. Fig. 1 is an illustration of the near-Earth orbital debris environment and the sources of data currently used by the ODPO to define the environment.

Orbital debris about 10 cm or larger in LEO, and about 1 m or larger in the geosynchronous orbit (GEO) region are tracked by the U.S. Space Surveillance Network and maintained in the U.S. Satellite Catalog. The ODPO maintains an on-going program that uses the Haystack, HAX, and Goldstone radars to collect data for orbital debris as small as several millimeters in LEO. For orbital debris smaller than 1 millimeter in LEO, space-based in situ measurements and the inspection of external hardware surfaces returned from space are the only options. The most recent data on the sub-millimeter orbital debris population came from the inspection of the Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) radiator surface (exposed to space between 1993 and 2009) and the window and radiator panels of the Orbiter from Space Shuttle missions between 1995 and 2011. Since sub-millimeter orbital debris evolve rapidly in the LEO environment, updated data are needed on a regular basis to better define the population and to quantify the risk to operational spacecraft.

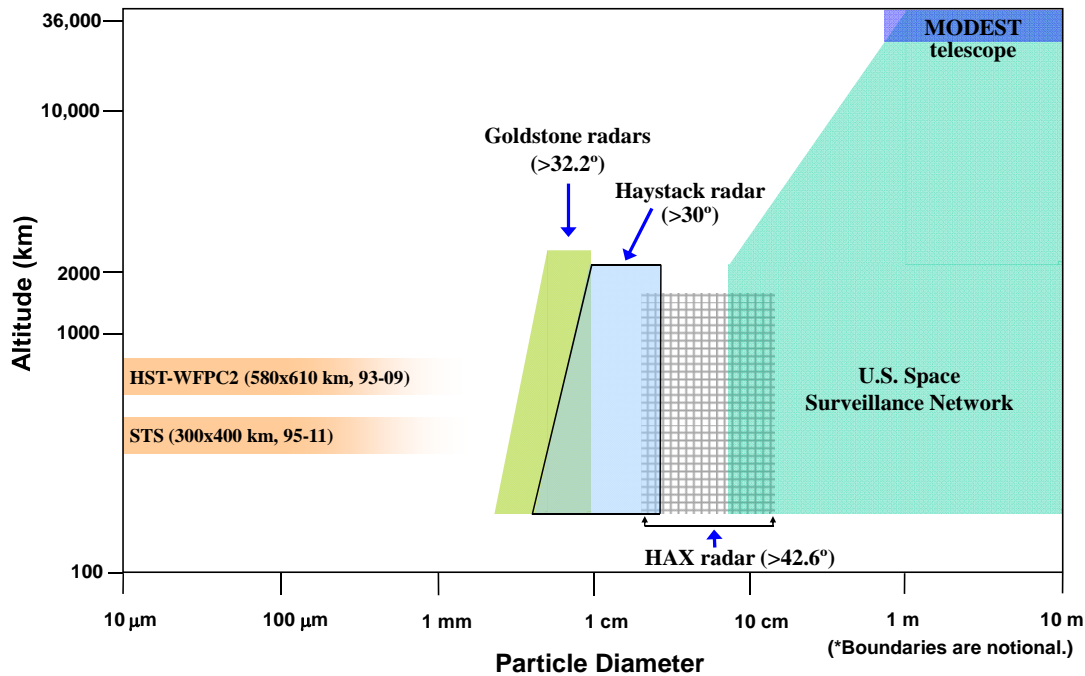


Figure 1. Sources of the MMOD data used by the NASA Orbital Debris Program Office. Boundaries of the coverage areas are notional. Ground-based radar data are also limited by the location (latitude) of the radar facility. The only recent data available on sub-millimeter particles are from the HST WFPC2 radiator surface inspection and Space Shuttle window and radiator panel inspections.

A key difficulty for in situ measurements of small MMOD is achieving a detection area large enough and exposure time long enough to collect sufficient data for meaningful statistical sampling of the population. The orbital debris detection efficiency is illustrated in Fig. 2, where the fluxes at different altitudes are shown. The curves are based on the NASA Orbital Debris Engineering Model (ORDEM) 3.0 for the year 2016. The bold curves are the predicted fluxes and the thin curves are the one-sigma standard deviation uncertainties associated with the predictions. Orbital debris flux is very sensitive to the orientation of the detection surface. To maximize the number of detections, the sensing surface must face the ram direction. This orientation also has the advantage of minimum micrometeoroid impacts. For a two-year mission at 400 km altitude, a minimum detection area of 1 m² is needed to sample orbital debris in the 50 to 100 μm size regime. For a two-year mission at 700 to 900 km altitude, a minimum detection area of 1 m² is needed to sample orbital debris in the 500 μm to 1 mm size regime.

To address the lack of new data for orbital debris in the millimeter and smaller size regime, the ODPO has supported the development of a particle impact detection sensor, Debris Resistive/Acoustic Grid Orbital Navy-NASA Sensor (DRAGONS), since 2002. The early DRAGONS technology development was also funded, via two multi-year proposal awards, by the NASA Science Mission Directorate (SMD) and the NASA Exploration System Mission Directorate (ESMD). The DRAGONS team consists of members from several organizations, including the NASA ODPO, the U.S. Naval Academy (USNA), the U.S. Naval Research Laboratory (NRL), University of Kent in Great Britain, Virginia Tech (VT), the NASA Hypervelocity Impact Technology (HVIT) group, and Jacobs. The ODPO proposed DRAGONS as an external payload on the ISS to the ISS Technology Demonstration Office in 2013. The proposal was accepted, including the payload funding support, by the ISS Program in early 2015. The plan is to deploy a 1 m² DRAGONS on the ISS in late 2016 for a two- to three-year mission duration. To avoid unnecessary confusion with SpaceX's Dragon launch vehicle, which will carry DRAGONS to the ISS, the project name used for the ISS DRAGONS mission is Space Debris Sensor (SDS).

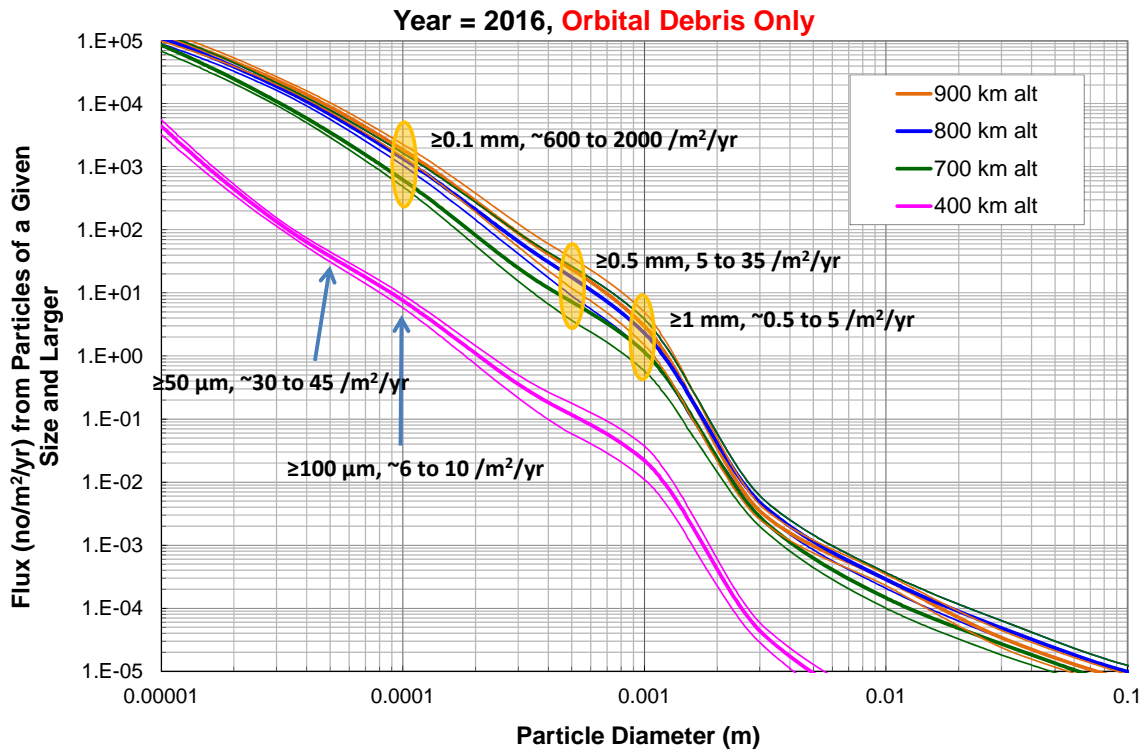


Figure 2. The orbital debris flux predictions at different altitudes. The calculations are based on the NASA ORDEM 3.0 model for the year 2016. The bold curves are the predicted fluxes and the thin curves are the one-sigma standard deviation uncertainties.

2. SYSTEM OVERVIEW AND SUBSYSTEMS

2.1 DRAGONS System Overview

The basic structure of a DRAGONS unit is illustrated in Fig 3. There are two thin films located 15 cm apart. A solid back plate is also placed at a short distance below the second thin film. Multiple acoustic impact sensors are attached to the thin films and the back plate. The surface of the top film is coated with long and thin resistive lines. When a hypervelocity MMOD particle, sufficiently larger than the thickness of the two thin films and the width of the resistive lines, hits the first film, it will cut several resistive lines, travel through the film, impact the second film, go through it, and then finally hit the back plate. The impact location on the top (or the bottom) film can be calculated with a simple triangulation algorithm based on the different signal arrival times measured by different acoustic sensors. Combining the impact timing and location data on the two films provides the impact speed and direction measurements of the impacting particle. Experiments have shown that, for thin film penetration, the damage area is approximately 5-10% larger than the size of the impacting particle. A more accurate correlation can be established by dedicated hypervelocity impact tests. Therefore, the resistance increase of the grid panel at the time of the impact (signaled by the acoustic sensors) indicates the number of line breaks, which is a good measure of the size of the damage area. When the particle finally hits the solid back plate, the impact kinetic energy can be estimated from the acoustic signals received by the sensors attached to the plate. When data from these measurements are processed and combined, information on the impact time, location, speed, direction, size of the impacting particle, and a simple estimate of the density of the impacting particle can be obtained.

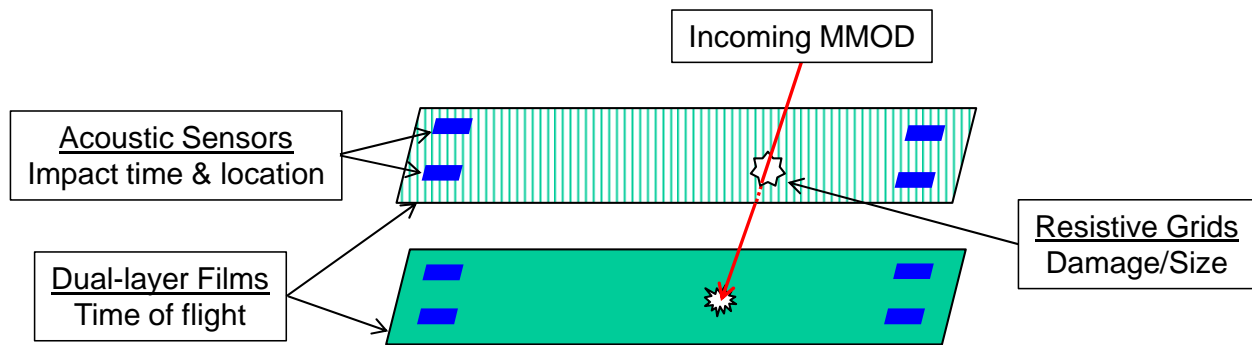


Figure 3. A simple illustration of the DRAGONS detection principles. A solid back plate can be added a short distance below the bottom film (not shown) to measure the impact kinetic energy, which, when combined with data from the acoustic sensors and the resistive grid, provides a simple estimate of the density of the impacting particle.

2.2 DRAGONS Concept and Technology Development

To improve the damage area measurement accuracy, resistive lines and the spacing between the lines must be as thin as possible with good quality control over the line width, line spacing, resistive material, and the characteristics of the resistive material over a wide temperature variation. Since 2009, various tests have been conducted to improve understanding of the resistive grid system. Different backing materials for the resistive grid have been considered, depending on their purpose. A thick, solid backing plate has the advantages of generating a large impact damage area at least several times the size of the impacting particle. This enables the detection of MMOD particles significantly smaller than the line width and line spacing. The impact acoustic signals on such a plate also allow for a direct measurement of the impact energy. However, a small impacting particle cannot penetrate the plate and the secondary ejecta generated after the impact could potentially damage nearby subsystems, such as the electronics. The early technology development started with test articles made of Duroid 6002 board material with a thickness of 5 mm. A grid of Ticer Technologies NiCrAlSi resistive material was photo-lithographed into 1500 62.5 μm resistive lines on the surface of each board. The resistive grid boards were then tested at the hypervelocity impact facility at the University of Kent to explore the characteristics of this thick plate configuration. While satisfactory, the structure of this composite system generated less than optimum penetration hole geometries.

A better option for the resistive grid backing material was later found to be a thin film. This configuration provides clean penetrations and line breakages. In addition, it allows the particle to penetrate the film and impact a second film some distance away, thus enabling impact direction and speed measurements. However, a finer resistive line width and line spacing are required for a more accurate measurement of the damage area. After testing different film materials and thicknesses, Kapton films with a thickness of 25 μm were identified as a good candidate. This configuration allows most 200 μm and larger MMOD particles to penetrate the top film, remain intact, and then impact a second film offset by 15 cm. Fig. 4 shows two impact test results on the 25- μm Kapton films coated with resistive lines. The left panel shows the damage by two 300 μm stainless steel spherical projectiles with an impact speed of 4.91 km/sec normal to the surface. The right panel shows the damage by a 1 mm stainless steel spherical projectile with an impact speed of 4.90 km/sec at a 45° impact angle to the surface. The impact direction was perpendicular to the resistive lines.

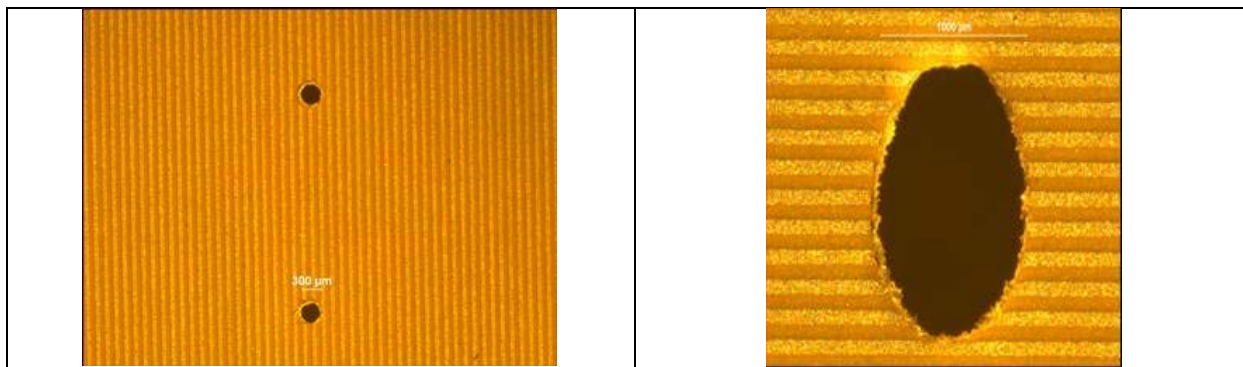


Figure 4. Hypervelocity impact tests on 25- μ m Kapton films coated with resistive lines conducted in 2011. Note the width and spacing of the resistive lines for this test series were 75 μ m.

The DRAGONS acoustic impact sensors are made of polyvinylidene fluoride (PVDF) material. The initial development of the sensors was funded by the NASA SMD's Planetary Instrument Definition and Development Program in 2003-2005 and then by the NASA SMD and ESMD LASER Program in 2009-2012. After several series of hypervelocity impact testing and analyses, PVDF was determined to be the best available sensor material for the intended applications to detect hypervelocity impacts by MMOD particles in space. Among the transducer materials evaluated during that period, PVDF has the highest sensitivity, lowest mass, and is available commercially as a thin, flexible sensor that is easily applied to a surface without significantly constraining the substrate. The piezoelectric nature of PVDF, unlike other system components, requires no electrical power for impact detection. In laboratory tests using small particle impacts, large electrical signals were generated by these sensors when attached to various substrate materials and analyses of the impact acoustic signals show that PVDF is indeed an excellent material for MMOD impact detections [3-4].

The nominal configuration for DRAGONS consists of four PVDF sensors attached to each subsection of the two Kapton films. The sensor data are collected for the time of flight calculation. Three PVDF sensors are sufficient for the triangulation of the impact location from relative signal arrival times, and the fourth one serves as a backup. Fig. 5 shows the hypervelocity impact facility at Kent and one set of example acoustic signals collected from the normal impact test described in Fig. 4.

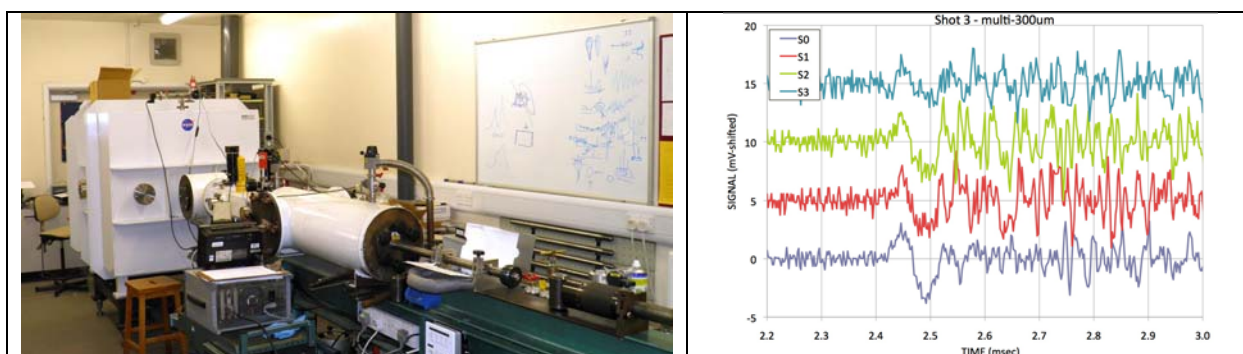


Figure 5. Left: The 2-stage light gas gun and the test chamber at the University of Kent. Right: Acoustic signals received at the four PVDF sensors attached to the backside of the Kapton film.

The combination of two thin film layers separated by a short distance and instrumented with PVDF acoustic sensors can be used to measure the MMOD impact speed and direction. Various configurations have been tested over the years and two examples are provided in Fig. 6. The left panel shows a test article from an impact test series conducted in 2004. The two Kapton films were separated by 10 cm and a multi-layer insulation sheet was placed behind the rear film to absorb the impacting particles and to prevent the

generation of secondary ejecta. A small piece of aerogel was also added for a different test objective. The right panel shows a test article from a test series conducted in 2012. In addition to the dual-thin-film system and the PVDF acoustic sensors, fiber optic displacement sensors were included to test their performance for a different objective.

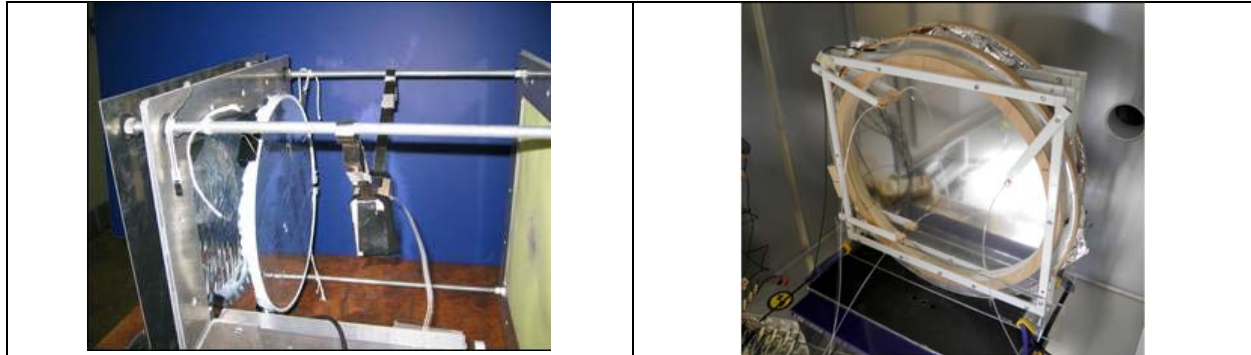


Figure 6. Left: A test series conducted in 2004. The test article consisted of dual-layer thin films with two PVDF acoustic sensors attached to each film and a piece of aerogel as the third component. Right: A test article used in 2012. The separation between the two films was 10 cm. In addition to PVDF sensors, fiber optic displacement sensors were included in this test series.

3. CURRENT STATUS

The near-term goal of DRAGONS is to advance its Technology Readiness Level (TRL) to 9 and to demonstrate the system capabilities of detecting and characterizing sub-millimeter MMOD impacts on the ISS. The long-term goal of DRAGONS is to identify opportunities to deploy DRAGONS to 800-1000 km altitude to better define the small orbital debris environment in LEO and to also potentially deploy DRAGONS to GEO to explore the unknown small debris environment there. Since the selection of DRAGONS for the SDS deployment opportunity, the focus has been on system development to meet a very demanding ISS payload schedule. New hypervelocity impact test series have also been initiated at the NASA White Sands Test Facilities. The DRAGONS SDS project team completed the Preliminary Design Review (PDR) on 14 May 2015. The Critical Design Review (CDR) is scheduled for February 2016. The instrument delivery is in May 2016, for a launch to the ISS in August 2016.

4. REFERENCES

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